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# An Enhanced Personal Cooling Garment for Aircrew

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## SUMMARY

A novel enhanced personal cooling garment (EC) for aircrew was tested on seven male subjects who were clad in full immersion protective aircrew clothing and exposed to 40C and 20% relative humidity for three hours. For comparative purposes, the subjects also wore current air-cooling vest (AC) alone. Two test protocols were used. One protocol provided the subjects with personal cooling throughout the three-hour trial; the other protocol did not allow the subjects to use their personal cooling for the first hour of the three-hour trial. The enhanced personal cooling garment prototype was shown to enhance the level of cooling provided by existing air-cooled vests, thus providing potential physiological benefits and hence greater comfort to aircrew.

## INTRODUCTION

Aircrew conducting flight operations in hot environments are susceptible to heat stress. Heat stress can invoke physiological and psychological responses that are dangerous to aircrew performance and hence safety [1,2].

Current approaches to aircrew cooling involve either liquid (LC) or air cooled (AC) garments. LC vests are worn by helicopter crews and astronauts. A typical system is comprised of a two-liter block of ice acting as a heat sink, and a garment fitted with a network of tubing through which chilled water is circulated by a small DC-powered pump. Cooling is due primarily to conductive heat transfer from the skin and clothing microenvironment to the water, across the tubing wall. While such systems are portable and robust, they are heavy (≈ 4 kg) and require frozen water and electrical power. They offer limited heat extraction; good performance requires tubing to remain in contact with the body.

AC vests distribute low-pressure air over the aircrew member's torso. AC vests are worn in aircraft offering conditioned airflow. Typically, AC vests consist of a spacer material sandwiched between perforated air impermeable fabrics through which climate controlled air is passed. AC systems generally provide higher amounts of cooling and keep the wearer drier than LC systems.

Mustang Survival Corporation recently developed a prototype Enhanced Personal Cooling Garment (EC) which uses a different approach than existing AC or LC [3,4]. The EC vest is constructed and worn in a manner that positions a thin layer of water next to the wearer's skin. The vest is constructed of highly vapour permeable, yet liquid impermeable fabrics. When filled with water, it remains thin (<2mm) to minimize the inherent insulation of the EC garment itself. Preliminary testing by Mustang Survival showed cooling is achieved as water diffusing from the vest extracts its heat of vaporization from the fabric layers. The EC vest is lightweight (0.4 kg empty and 0.9 kg filled) with no moving parts.

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Tests on a guarded sweating hot plate indicated that when EC was worn below AC, the combination was capable of providing higher heat loss than AC alone. Tests also showed moisture introduced beneath EC will also diffuse through the vest. Based on these preliminary findings, full human subject testing was considered as necessary to further quantify and validate the vest's potential as an enhanced personal cooling garment for aircrew. This paper details the methods and results from human subject tests [5].

## METHODS

### *Subjects*

Seven healthy, non heat-acclimated male volunteers comprised two test groups. Three of the subjects (group N) experienced greater heat stress by depriving them of cooling for the first hour of the test. Four of the subjects (group C) were provided with cooling throughout the duration of three-hour trial.

Mean values (±SD) for age, weight, height, and chest circumference for group N subjects were 22.7±1.7 yrs, 74.3±10.7 kg, 171.5±1.7 cm and 96.4±8.3 cm, respectively. Mean values (±SD) for age, weight, height, and chest circumference for group C subjects were 26.8±3.7 yrs, 79.7±14.6 kg, 178.6±8.5 cm and 99.8±7.4 cm, respectively. All subjects were provided with an information sheet outlining experimental details and risks and signed an informed consent form prior to commencing any tests. Additionally, all subjects were instructed not to consume caffeine for 12 hours prior to testing and alcohol for 24 hours prior to testing.

### *Experimental Protocol*

All subjects participated in two test sessions, one trial with air cooling alone (AC) and another with both air and enhanced cooling (EC) separated by a minimum of two days (in random order). Each subject wore briefs, cotton-polyester long underwear, wool socks, leather flight boots, aviation immersion coveralls (Mustang MAC 200), flight gloves, life preserver and survival vest (Mustang MSV971), flight helmet, anti-G trousers (CSU-13 B/P), AC vest (Mustang MSF833) either with or without the prototype EC vest. Each subject was seated in an ejection seat within an environmental chamber at 40.1±0.1°C and 19.8±1.8% RH with a fan providing a wind speed less than 0.1 $m \cdot s^{-1}$. All subjects were provided with 1 litre of water to drink over the course of the experiment (if necessary) and allowed to view a movie of their choice. Test termination criteria was set as either reaching a duration of 3 hrs, the subject's rectal temperature exceeding 39°C (or 2°C above initial temperature), the subject exhibiting symptoms of dizziness, nausea, or weakness, the subject asking to withdraw, or the experimenter deciding to terminate the experiment.

### *Description of Cooling Systems*

The AC vest was a Mustang Survival MSF833. The bladder of the AC vest is made from two layers of impermeable polyurethane-coated nylon separated by a spacer material that acts as an air distribution manifold. The innermost layer of the polyurethane-coated nylon is perforated to direct escaping air towards the wearer's body. A second layer of spacer material between the perforated fabric and body ensures air distribution over the torso. The vest exterior is covered with aramid cloth. Cool air for AC was provided by blowing air through a heat exchanger immersed in an ice bath maintained at 2-5°C. This yielded a flow rate of 393.6±8.5 $L \cdot min^{-1}$ (13.9±0.3 SCFM) at a vest inlet temperature of 23.2±0.5°C.

The EC garment was a front-zippered vest made of vapour permeable, polyurethane-coated stretch nylon, radio frequency welded to produce a network of channels through which water could migrate under capillary action. Water entered the vest through an inlet valve at the waist and trapped air was vented from three PTFE patches located at shoulder level. The EC was connected to a water reservoir suspended 1.4 m (4.6 ft) above the vest inlet to produce a maximum hydrostatic pressure of approximately 14 kPa (2 psi). Once connected to the reservoir, EC was self-filling, drawing water from the reservoir only as it evaporated from the vest. Water consumption was measured by periodically recording the reservoir water level. The vest was fit snug by adjusting speed lacing along the shoulders and edges of the front zipper.

*Dressing and Weighing Procedures*

Subject preparation involved subjects instrumenting themselves with a rectal thermistor (inserted 15 cm) and weighing themselves to determine pre-trial nude weights (with thermistor), while their briefs were weighed separately in a plastic bag. Wearing shorts, the subjects were instrumented with heart rate electrodes, temperature thermistors at six sites and heat flux transducers at five sites. All articles of clothing were individually weighed in plastic bags and handed to the subject for immediate donning. Prior to the subject entering the environmental chamber, a bottle of water was weighed and given to the subject for consumption during the test (if desired).

Immediately following termination of the experiment (within 10 minutes) each article of clothing was again individually weighed in a plastic bag and the subject's nude weight recorded prior to removal of the rectal thermistor. Additionally, the subject's water bottle was weighed to determine the amount of water consumed during the trial for later correction of the subject's post-trial nude weight. Sweat production was calculated as the difference between corrected pre-trial and post-trial subject nude weights.

*Data Acquisition*

Data from all temperature thermistors (YSI 400) and heat flux transducers (Concept Engineering) along with the cooling vest air inlet temperature, environmental chamber temperature and relative humidity were recorded every minute by a remote data logger (Grant 1250 series Squirrel meter/logger). Values for all of the above as well as core temperature, cooling air flow rate, and heart rate were recorded manually at ten minute intervals.

*Ratings of Thermal Comfort*

Thermal comfort was rated by the subject on a scale of 1 (so cold I am helpless) to 13 (so hot I am sick and nauseous) at ten minute intervals.

*Statistical Analyses*

All data are presented as mean values and the standard deviation of the mean. Mean skin temperature and heat flux is weighted by skin surface area. A one-tailed paired T-test (95% confidence level) was used to compare C-AC to C-EC and N-AC to N-EC. ANOVA and Tukey-Kramer post-hoc analysis was used for comparison between groups.

## RESULTS

*Heart Rate*

Figure 1 shows the average heart rate of group C and N. During the final two hours of the test, mean heart rate of group N was very significantly lower wearing EC than AC ($p<0.005$). The mean heart rate of group C was also significantly lower wearing EC than AC ($p<0.0001$). Note that during the final hour of testing, mean heart rate of group N-EC was comparable to that of C-AC and C-EC.

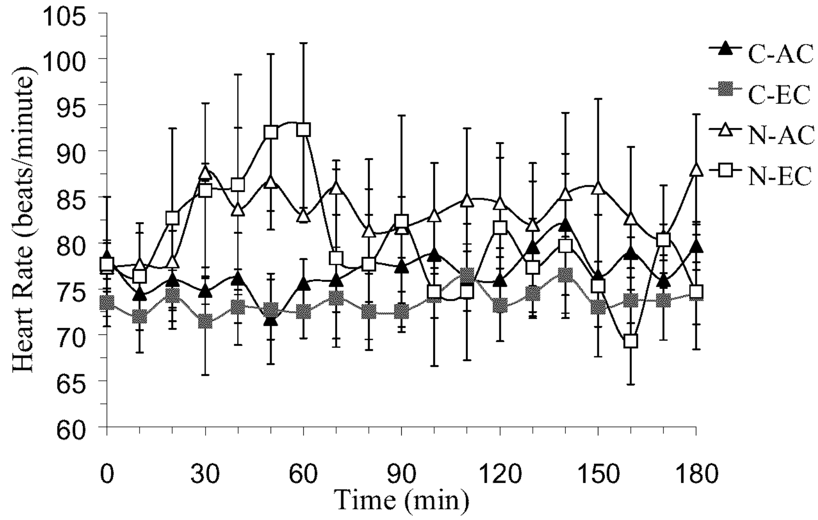


**Figure 1 – Heart Rate**

*Rectal Temperature*

Figure 2 shows the mean change in rectal temperature of group C and N.

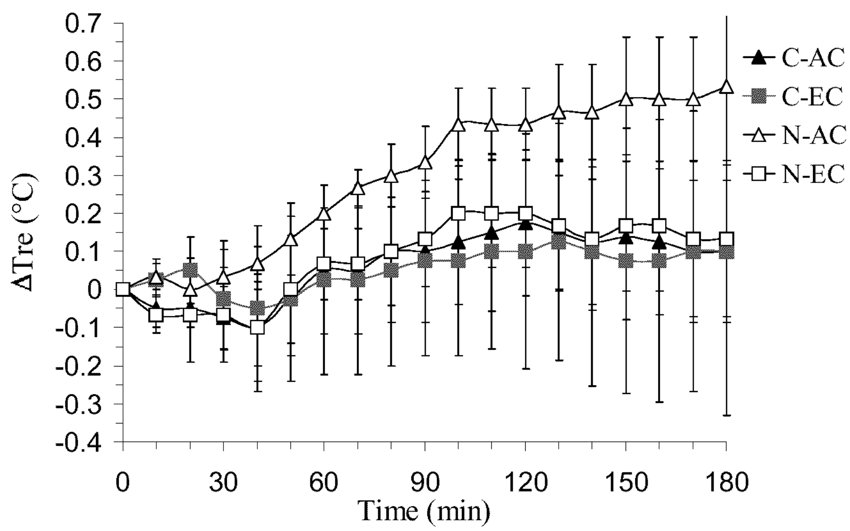


**Figure 2 – Change in Rectal Temperature**

The greatest increase in mean rectal temperature was observed with group N wearing AC. The mean change in core temperature of group N was significantly lower while wearing EC than AC ($p<0.0001$). For group C, mean change in core temperature was not significantly different between AC and EC ($p>0.05$). It is of interest to note that mean change in core temperature of group N-EC (whose protocol subjected them to greater heat stress) not significantly different from group C ($p>0.05$).

*Mean Skin Temperature of Cooled Sites*

Figure 3 shows the mean skin temperature of the cooled sites for group C and N. These two sites were the abdomen and mid-back. The highest mean skin temperature of the cooled sites was observed for group N during the first hour in which no cooling was provided. With both group C and N, the mean skin temperature of the cooled sites was significantly lower wearing EC than AC ($p<0.0001$). Note that within 20 minutes of activating EC, group N exhibited mean skin temperatures of the cooled sites comparable to those of group C-AC. After one hour of activating EC, mean skin temperatures of the cooled sites of group N-EC were comparable to those of group C-EC. Once cooling is activated, both groups using EC had lower skin temperatures than AC.

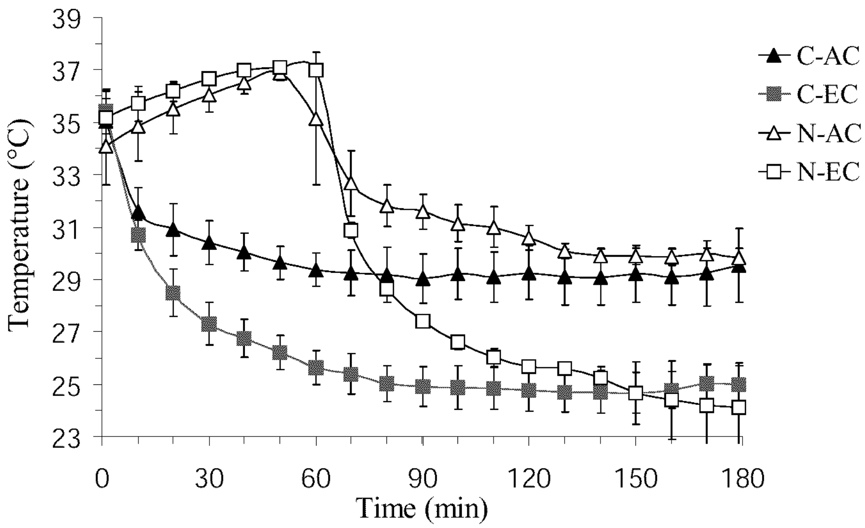


**Figure 3 - Mean Skin Temp (cooled sites)**

*Mean Skin Temperature of Uncooled Sites*

Figure 4 shows the mean skin temperature of the uncooled sites for group C and N. The four sites were the calf, thigh, bicep and forearm.

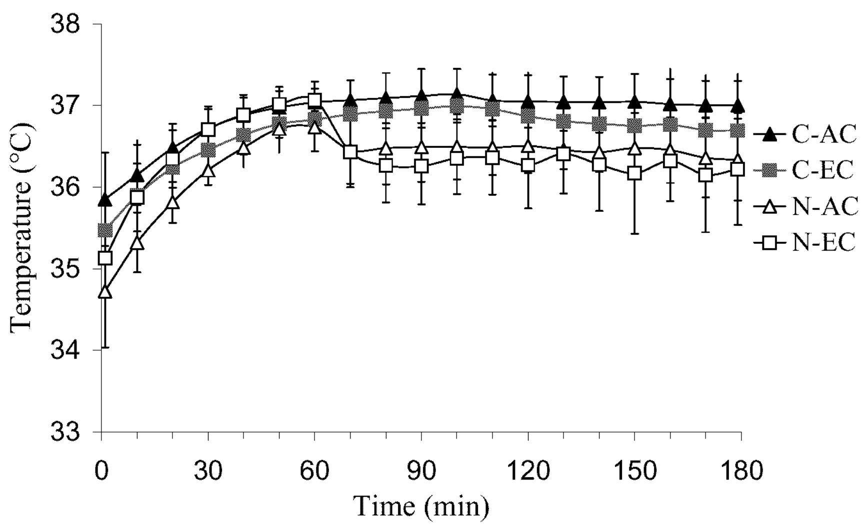


**Figure 4 - Mean Skin Temp (uncooled sites)**

The mean skin temperature of the uncooled sites of group N was significantly lower with EC than AC ($p<0.01$). With group C, the mean skin temperature of the uncooled sites was significantly lower with EC than AC ($p<0.0001$).

*Mean Heat Flow of Cooled Sites*

Figure 5 shows the mean heat flow of the cooled sites for group C and N. These two sites were the abdomen and mid-back.

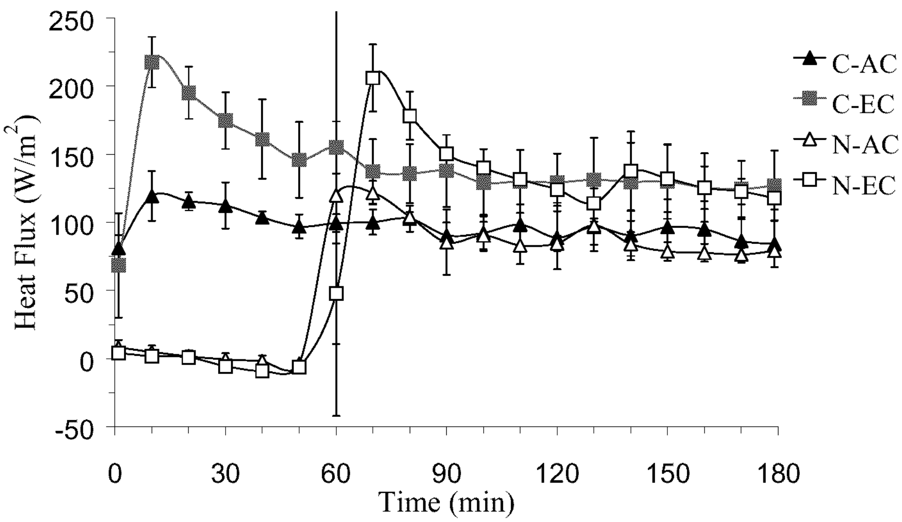


**Figure 5 - Mean Heat Flow (cooled sites)**

During the first hour, group C had higher mean heat loss from the cooled sites than group N. During the first hour, group N had essentially no heat loss from cooled sites rather these sites exhibited heat gain. This was as expected as cooling was not activated during the first hour for group N. Group C had significantly greater mean heat loss from cooled sites while wearing EC than AC ($p<0.0001$). During the last two hours, group N had significantly greater mean heat loss from cooled sites while wearing EC than AC ($p<0.001$). .

Upon activation of cooling, mean heat loss from the sites beneath EC was greater than beneath AC, regardless of group. Mean heat loss from cooled sites of EC was approximately 50 $W{\cdot}m^{-2}$ (or 50%) greater than AC.

*Mean Heat Flow of Uncooled Sites*

Figure 6 shows mean heat flow of the uncooled sites for group C and N. These three sites were the thigh, bicep and forearm. During the first hour, mean heat flow from the uncooled sites was not significantly different between groups. For group C, mean heat flow from the uncooled sites was significantly higher with EC than AC ($p<0.0001$). For group N, mean heat flow from the uncooled sites was significantly higher with AC than EC ($p<0.0001$).

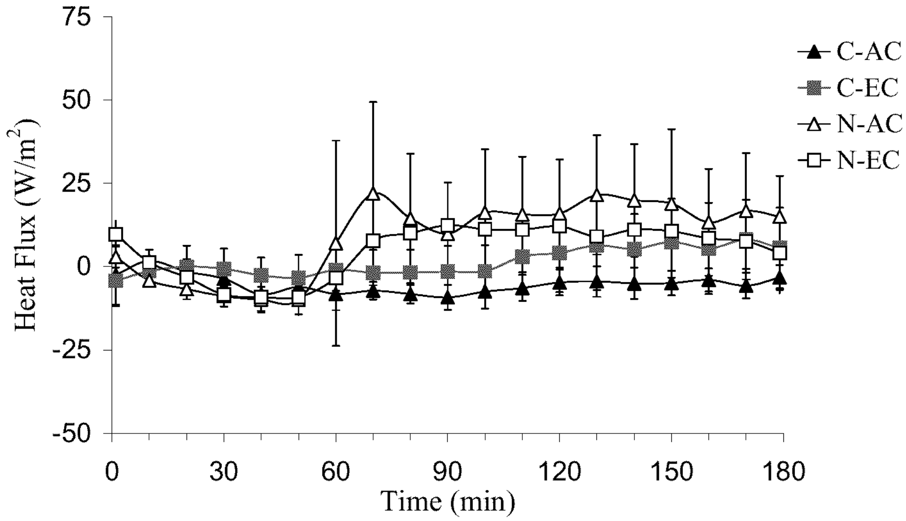


**Figure 6 - Mean Heat Flow (uncooled sites)**

*Rating of Thermal Comfort*

Ratings of thermal comfort for group C and N are shown in Figure 7.

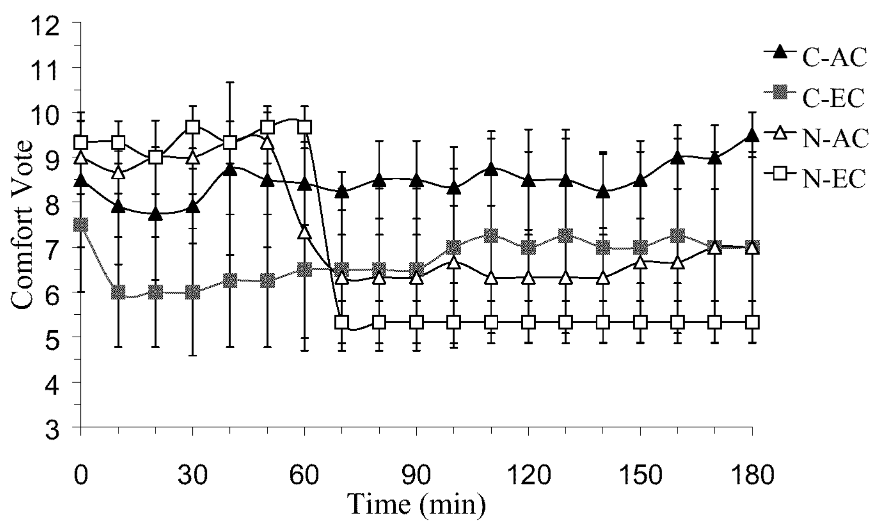


**Figure 7 - Rating of Thermal Comfort**

During the first hour, group N rated themselves as warmer than group C. This is consistent with expected differences due to protocol. With EC, group C and N felt significantly cooler ($p<0.0001$ and $p<0.005$, respectively) than with AC.

*Hydration Status*

Changes in nude body weight for group C and N are shown in Table 1.

**Table 1 – Body and clothing weight change**

| *Group-Vest* | *Body Weight Loss (g)* | *Clothing Weight Change (g)* |
|---|---|---|
| C-AC | 600.8 ± 315.0 | -80.6 ± 79.9 |
| C-EC | 362.9 ± 184.0 | -4.3 ± 53.0 |
| N-AC | 566.8 ± 34.4 | 26.6 ± 88.8 |
| N-EC | 604.8 ± 226.0 | 107.8 ± 63.8 |

There were minimal differences between body weight loss with C-AC, N-AC and N-EC. Group C wearing EC lost considerably less weight due to sweating and respiration than the others. It is possible that lower skin temperatures reduced the sweating response.

With Group C, clothing weights were less after completion of testing than before. With Group N, the clothing weights increased for both AC and EC. This is likely due to greater sweating induced by the one-hour heat stress of Group N. Within a given group clothing remained drier with AC than EC. This is probably due EC introducing moisture to the clothing microenvironment.

## DISCUSSION

The findings from the present study show the effectiveness of both air-cooling and a prototype air-liquid cooling system when worn beneath full military aircrew clothing ensembles. The enhanced cooling system (EC) provided a greater cooling capability than air-cooling alone. Use of EC resulted in reduced heart rates, lower rectal and skin temperatures, greater heat loss from the body and improved thermal comfort than with use of AC alone.

The current prototype EC system is lightweight and can easily integrate into existent aircrew clothing ensembles. The logistics of providing water to the vest require further consideration. Currently, the vest can be filled and detached from its reservoir, although this would limit its operational duration. When left connected to a low-pressure reservoir the vest is capable of self-replenishing hence its operational duration would depend on reservoir volume. Hot plate testing and preliminary human testing indicates the EC vest provides cooling without the presence of AC. Its cooling capacity is dependent on the water vapour pressure gradient between the plate and ambient environment. The magnitude of passive cooling has been quantified on a sweating hot plate but not on human subjects. This capability may offer cooling outside the cockpit environment during transit to and from aircraft as well as post-ejection.

The durability and hence leak-tightness of the vest during maneuvers which induce high G-load in the cockpit requires investigation. While the vest is still at an early prototype stage, its performance is promising and warrants further investigation.

## CONCLUSION

Based on limited human subject testing, it is concluded that the prototype Enhanced Personal Cooling Garment (EC) provided significantly lower mean core and skin temperatures than AC alone. Heart rate was significant lower with subjects wearing EC than AC and test subjects rated themselves as significantly cooler while wearing EC than AC. This was due to significantly greater heat loss from the torso wearing EC than AC. The EC prototype was found to enhance the level of cooling provided by a typical aircrew AC vest.

## ACKNOWLEDGEMENTS

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